DISTRIBUTION OF THE ELECTRON CONCENTRATION AND WAVE PROCESSES IN A PULSED DISCHARGE

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A quantitative Schlieren method for measuring the electron-density gradient using a laser source in the infrared range is described, which guarantees measurement of densities above 10^{14} cm^{-2}; a detailed observation of the profile of the gas ionization in a pulsed discharge is likewise described. Certain results are presented of a study of the distribution of the electron concentration over the cross section of the discharge tube in a straight argon discharge during the flow of discharge current and also during the subsequent stages of the process. In order to perform time measurement of the electron-density gradients and to construct an overall picture of the plasma distribution, the Schlieren method with a CO_2 laser (10.6 μ) as a light source was used. The measurements that were carried out revealed a complex picture involving the formation of a series of successive radial compression waves that exist during a fairly long period after completion of the discharge.

The processes that occur in a straight pulsed discharge are currently once more attracting attention in connection with the choice of the operating mode of powerful gas lasers [1-4]. It seems probable that in pulse modes not only the primary process (the electrical discharge) but also a series of secondary phenomena (shock waves, recombination, chemical reactions, etc.) participate in the excitation of inversion. The existence of hydrodynamic perturbations in straight discharges was recorded in a number of papers [5, 6]. Shock waves and compression waves may evoke additional population inversion via ionization and subsequent electronic excitation of atoms and molecules. Under these conditions densities of the order of 10^{16}-10^{17} cm^{-3} are of greatest interest, since at lower densities it is difficult to obtain a noticeable gain in a gas-discharge laser, while at higher densities inversion is rapidly disrupted by collisions of the second kind.

The refractive index N of the plasma is determined by the resultant contribution of its neutral n_0 and charged n_e components

$$N-1=-An_e\lambda^2+(B+C/\lambda^2)n_0 \qquad (A=4.46\cdot10^{-14}) \tag{1}$$

Here λ is the wavelength; B and C are constants that are characteristic for a given atom or ion. From Eq. (1) it is evident that

$$\frac{dN}{dn_e}=-A\lambda^2, \qquad \frac{dN}{dn_0}=B+\frac{C}{\lambda^2} \tag{2}$$

Consequently, the transition to measurements in the long-wave portion of the spectrum is of fundamental significance, since under these conditions the sensitivity to the electron component increases abruptly. Moreover, measurements of the infrared range allow relatively low concentrations of electron to be determined against the background of a predominant neutral component in a weakly ionized plasma. The

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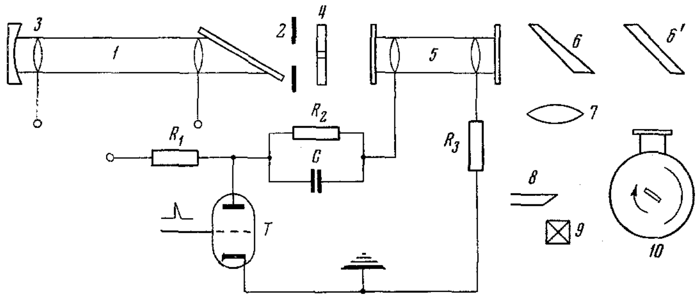

Fig. 1

appearance of an electron-density gradient in the plasma in a direction perpendicular to the direction of the probing light beam leads to deflection of the beam through an angle

$$\beta = -A\lambda^2 L \nabla n_e \qquad (3)$$

where L is the length of the perturbation region along the direction of the light beam.

The scheme of the experimental installation is depicted in Fig. 1. A CO_2 laser 1 having a power rating of 20 W and gas circulation was used in the work; 2, 3 are the mirrors of the laser. An irised diaphragm was introduced into the resonator cavity in order to suppress higher-order modes. This allowed the dimensions of the focal spot at the system output to be reduced and likewise permitted the elimination of beats that otherwise develop sporadically in the laser radiation. The radiation exited through an aperture having a diameter of 2 mm in one of the mirrors.

The plasma created in the gas-discharge tube 5 having barium fluoride windows was probed. The gas-discharge gap was 24 cm, and the inside diameter of the tube was 17 mm. A stationary longitudinal glow discharge was created in the tube, and pulse discharges between the same electrodes were periodically superimposed on it. The presence of a fixed current channel ensures symmetry of pulse discharges relative to the tube axis and causes good replicability of the conditions under which the discharges occur. The current of the glow discharge is produced by a rectifier and is limited by the resistor R_2. The voltage dropped across this resistor likewise charges the capacitor C. When a firing pulse is applied to the grid of the thyratron T the capacitor discharges into the discharge tube through the thyratron.

The beam from the CO_2 laser, after passing through the tube, is incident on a salt plate 6 which directs 1% of the incident flux onto the lens 7 which is made of barium fluoride and has a focal distance of 30 cm; the lens focuses the radiation onto the blade of the "knife" 8. The dimensions of the focal spot are 0.3 mm; the knife covers one-half of the focal spot. The radiation is recorded by the Ge(Au) photoresistor 9, which is cooled with liquid nitrogen. The dynamics of the discharge is recorded according to a self-luminescence using a driven streak camera 10 in the slit-sweep mode simultaneously with observation of the Schlieren effect. The experiment was carried out for $C = 0.5\ \mu F$, $R_1 = +10\ k\Omega$, $R_2 = 1400\ k\Omega$, $R_3 = 3\ \Omega$.

A quantitative interpretation of the Schlieren effect was achieved as follows. The distribution of the illumination J of the focal spot along the x axis perpendicular to the optic axis of the system and the edge of the knife was determined by scanning the spot by the knife edge using a micrometer screw. From the resulting distributions J(x) a graph was plotted of the integral function

$$\Phi(x) = \int_0^x J(x)\,dx$$

As a result of the Schlieren effect the quantity

$$z = \Phi(x) - \Phi(x_0)$$

was recorded, where x_0 is the position of the knife edge corresponding to the center of the focal spot. This allowed the magnitude of the linear displacement $x - x_0 = \beta f$ to be determined graphically, where f is the focal distance of the lens; then the value of the electron-density gradient dn_e/dr can be determined in terms

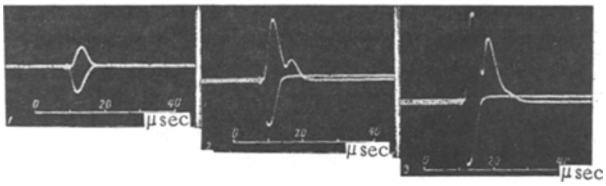

Fig. 2

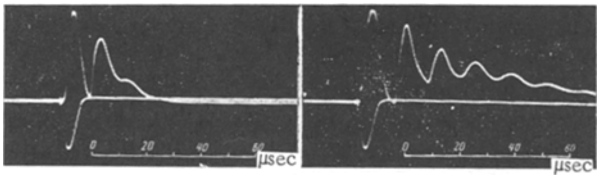

Fig. 3

of this displacement, where r is the distance from the tube axis to the probed sector. In view of the fact that even in a steady-state operating mode the radiation power of a CO_2 laser fluctuates within the limits of from 10 to 20%, the overall intensity was monitored. For this purpose the laser was supplied from a rectified unfiltered voltage at a frequency of 100 Hz.

At the instants corresponding to the zero-crossings of the voltage, lasing ceases, and therefore the time pattern of the lasing consists of sharply separated pulses having a length ~ 7 msec and a frequency of 100 Hz. The observation of the Schlieren effect is carried out on the top of one of these pulses. Since the duration of the sweep is 50 to 100 μsec under these conditions, the variation of the overall radiation intensity during this time interval may be neglected. The sweep line is displaced relative to the normal position by an amount equal to the height z_0 of the lasing pulse. In the calculation procedure described above the quantity z was replaced by the dimensionless ratio z/z_0, which assured independence of the results obtained from fluctuations of laser intensity. Oscillographing of the current through the gas-discharge tube was performed in parallel with this procedure.

A characteristic feature of the resulting oscillograms is the presence of a second maximum of the Schlieren signal after the current has ended. The magnitude of this signal increases with increasing pulse current through the tube; Fig. 2 displays oscillograms of the Schlieren signal and the discharge current for $p = 0.5$ torr and tube voltages $U = 2, 3, 4$ kV for frames 1, 2, 3, respectively; Fig. 3 shows the same thing for $U = 3$ kV and $p = 1, 2$ torr for frames 1 and 2.

High-speed slit sweeps of the self-luminescence of the discharge register a series of intense radial perturbations existing in the tube after completion of the discharge. An analysis of the oscillograms and sweeps of the gas luminescence shows that the second ionization maximum is associated with a shock wave that converges toward the center. The velocity of the shock wave was calculated as the ratio between double the distance from a point near the axis to the wall and the time interval between the first and second maxima.

Let us present the values of the velocities W (km/sec) of the shock waves as a function of the voltage U (kV) and the pressure p (torr):

$$\begin{aligned} &W = 2.7,\ 3.1,\ 3.4 \text{ for } U = 3,\ 4,\ 5 \text{ for } p = 0.5 \\ &W = 1.9 \text{ for } \quad U = 3,\ p = 1 \\ &W = 1.4 \text{ for } \quad U = 3,\ p = 4 \end{aligned}$$

As might be expected, with increasing pressure the average shock-wave velocity decreases. The oscillograms of the Schlieren signal for an increase in pressure showed the presence of a whole series of successive radial perturbations. The high-speed sweep at these pressures likewise shows the formation of a series of successive radial compression waves existing during a time that is 5 to 20 times as long as the duration of the discharge; in Fig. 4 such a self-luminescence sweep of the discharge is shown for $p = 2$ torr, $U = 3$ kV.

Oscillographing of the time dependences of the Schlieren effect for a radial displacement of the probing laser beam parallel to the tube axis was carried out. When the beam crossed the tube axis the observed deviation z changed sign, which was evidence of the symmetry of the discharge relative to the axis (Fig. 5 displays the radial dependence of the Schlieren signal).

From the results of measurements at various radii the radial distribution of the electron density at various stages of the process was plotted by calculating the integral function

$$\int_0^r \frac{dn_e}{dr}\, dr$$

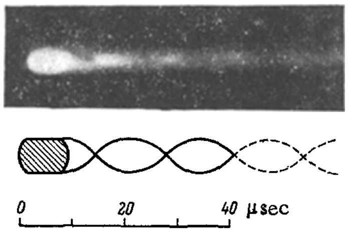

Fig. 4

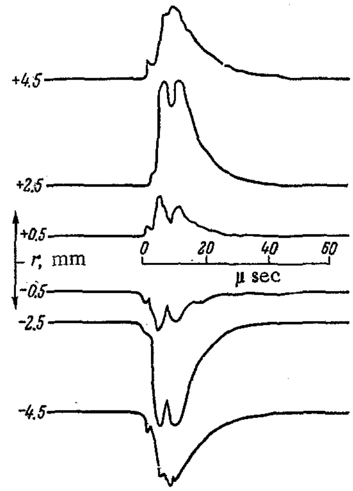

Fig. 5

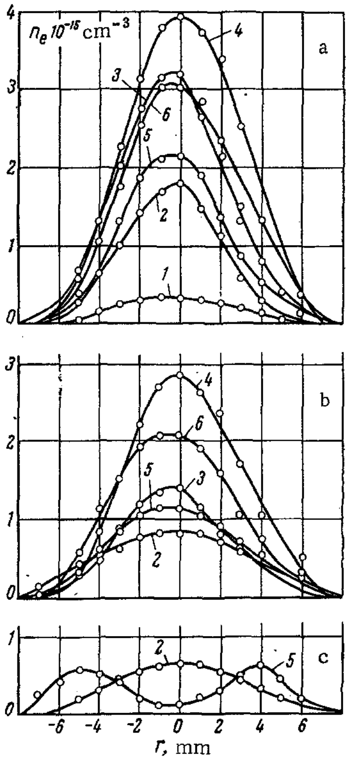

Fig. 6

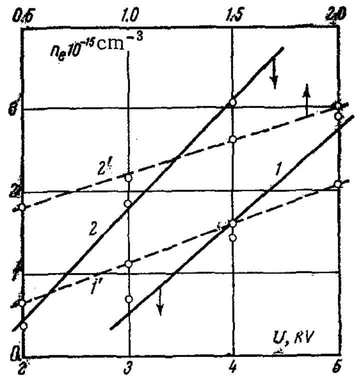

Fig. 7

Figure 6 displays the profiles obtained in this manner at the instant corresponding to the first (a) and second (b) ionization maxima, as well as at an instant when the convergent wave has not yet approached the center of the tube (the instant of the first ionization maximum (c)). At low pressures the wave merely "flattens out" the ionization profile, while for an increase in the initial pressure in the discharge tube the shock-wave front may be observed directly according to the shape of the electron-density profile. Figure 7 shows the dependence of the maximum ionization n_e on the pressure p for U = 3 kV and likewise on the voltage U across the tube at p = 0.5 torr at the instant corresponding to the first and second maxima on the tube axis.

In parallel with measurement of the Schlieren effect interferometry was carried out of the same plasma in a mode of photometric counting of the bands on a Michelson interferometer using a CO_2 laser as a light source. The results obtained are in good agreement with those presented above. It should, however, be noted that for operation in a mode of photoelectric counting of the bands, distortions associated with the Schlieren effect that is manifested simultaneously with the phase shift were observed on the oscillograms. Let us likewise note the fact that the relative role of the Schlieren effect increases when the transition is made to the infrared region of the spectrum.

Actually, the magnitude of the phase shift $\Delta\varphi$ of a light wave that has traversed the distance L in the plasma is

$$\Delta\varphi = \frac{2\pi}{\lambda}(N-1)L = -2\pi A n_e L\lambda \quad (4)$$

The Schlieren signal is proportional to the angle β for uniform illumination. A comparison of Eqs. (3) and (4) yields

$$\frac{\beta}{\Delta\varphi} = \frac{\lambda}{2\pi}\frac{\nabla n_e}{n_e} \tag{5}$$

It is useful to perform a comparative estimate of the sensitivity of determining the electron concentration by interferometry and using Schlieren measurements. Let us assume that we are able reliably to record a fraction 1/t of the band. Then from Eq. (4) we have the following relationship for the minimal detectable electron concentration:

$$n_e^{\min} = 1 / AL\lambda t \tag{6}$$

It is likewise natural to adopt the possibility of registering a change in overall intensity by the fraction 1/t as the criterion for the sensitivity of the Schlieren method. From Eq. (3) we have the following result for the minimal detectable electron-concentration gradient:

$$\nabla n_e^{\min} = S / 2AL\lambda^2 tf \tag{7}$$

where S is the size of the focal spot. From this we have

$$\frac{\nabla n_e^{\min}}{n_e^{\min}} = \frac{S}{2f\lambda} \tag{8}$$

In the linear approximation $\nabla n_e = n_e/r_0$, where r_0 is the effective radius of plasma formation. From this the condition for equality of the sensitivities of the two methods can be written in the form

$$r_0 S = 2f\lambda \tag{9}$$

The interferometric method is more sensitive for $r_0 S > 2f\lambda$, while the Schlieren method is more sensitive for $r_0 S < 2f\lambda$.

The substitution of specific parameters of the described experiment shows that the sensitivity of the Schlieren method is approximately four times as high in the case considered.

Thus, the quantitative Schlieren method using a laser source operating in the infrared range, which has been described above, ensures detailed observation of the state of the ionized gas in a pulse discharge. The observations which were carried out revealed a complex pattern of the wave processes in the discharge plasma. Radial compression waves caused abrupt fluctuations of the electron concentration in the discharge tube, and therefore the phenomena described above may play an essential role, for example, in the electrical excitation of inverse population in gas lasers operating in a pulsed supply mode.

LITERATURE CITED

1. R. K. Leonov, E. D. Protsenko, and Yu. M. Sapunov, "Certain results of investigating a pulsed argon gas laser," Opt. i Spektr., 21, No. 2 (1966).
2. V. M. Likhachev, M. S. Rabinovich, and V. M. Sutovskii, "On the possibility of studying a pinch-discharge according to the intrinsic simulated emission," ZhÉTF Pis. Red., 5, No. 2 (1967).
3. A. E. Hill, Multijoule pulses from CO_2 Lasers, Appl. Phys. Letter, 12, No. 9 (1968).
4. R. A. McFarlane and L. H. Fretz, "High-power operation of pulsed water-vapor laser and precision wavelength measurement of the strongest component," Appl. Phys. Letter, 14, No. 12 (1969).
5. Yu. G. Kozlov and A. M. Shukhtin, "Development of sound waves in a gas as a result of the passage of a current pulse," Zh. Tekh. Fiz., 38, No. 9 (1968).
6. I. V. Demenik, E. V. Mnuskin, N. I. Sereda, and D. P. Solovei, "Acoustic oscillations of a discharge channel in pulsed tubular flashlamps having large dimensions," Teplofiz. Vys. Temp., 8, No. 2 (1970).
7. R. W. Lutz and J. H. Kiefer, "Structure of the vibrational relaxation zone of shock waves in oxygen," Phys. Fluids, 9, No. 9 (1966).